WAVELENGTH DIVISION MULTIPLEXING AND DE-MULTIPLEXING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of Application No. 09/953,468, filed September 14, 2001.

TECHNICAL FIELD

The present invention relates generally to systems for wavelength division multiplexing, and more particularly to applying particular forms of optical gratings to multiplex, de-multiplex, interleave, and de-interleave multiple light wavelengths.

BACKGROUND ART

Optical technology is progressing rapidly. Growing needs, particularly in the telecommunications industry, are driving this progress and there is currently a major impetus to improve existing optical systems and to develop new ones. Unfortunately, several major components still are not completely meeting manufacturing yield, field reliability, and operating capacity requirements. These failings have resulted in high costs in existing systems and are limiting the adoption of future systems. One such component is the optical grating.

FIG. 1a-b (background art) depict to variations of traditional gratings. As can be seen, the shape of the groove can vary. FIG. 1a shows square steps and FIG. 1b shows blazed triangles, but other shapes are also possible, e.g., sinusoidal shaped grooves, and the physics is essentially the same.

Such "traditional gratings" were initially made of glass with grooves, and a few are still produced in this manner today. This, however, has a number of disadvantages. For instance, the density of the grooves is limited by the capability of the ruling engine, and the quality of the grooves produced tends to decrease as elements of the ruling engine wear from usage. Production of this type of gratings is time consuming and difficult, and the cost of such gratings is therefore high.

Molded and holographic gratings were invented later on, and their production cost is

significantly lower than for glass gratings. Unfortunately, although suitable for many applications, these gratings tend to deteriorate in harsh environments. For example, in fiber optic communications, all optical components must operate for long periods of time in temperatures ranging from sub-zero to over eighty degrees Centigrade, and in humidity ranging from zero to 100 percent (see e.g., GR-468-CORE, Generic Reliability Assurance Requirements for Optoelectronic Devices Used In Telecommunications Equipment).

As can also be seen in FIG. 1a-b, traditional gratings have the property that light has to shine on the grating surface from above. This limits the useful diffraction effect of such gratings to only one dimension, and multiple units need to be assembled if multiple dimensions (axes of direction) are required.

One example of an application where the need to work with multiple wavelengths and axes is common, and growing, is wavelength division multiplexing and de-multiplexing (collectively, WDM) in fiber optic communications. The use of traditional gratings in WDM usually requires either adhesives or mechanical fixtures to keep the assembly intact. Alignment is also needed to make sure that the gratings diffract light in the proper directions. The resulting assemblies formed with such traditional gratings thus tend to be significantly larger than the optical fibers being worked with and mechanical connectors are needed for connection. All of these considerations, and others, increase the cost in a fiber optic communications system.

A relatively recent invention is the fiber Bragg grating. The fiber Bragg grating is a periodic perturbation in the refractive index which runs lengthwise in the core of a fiber waveguide. Based on the grating period, a Bragg grating reflects light within a narrow spectral band and transmits all other wavelengths which are present but outside that band. This makes Bragg gratings useful for light signal redirection, and they are now being widely used in WDM.

The typical fiber Bragg grating today is a germanium-doped optical fiber that has been exposed to ultraviolet (UV) light under a phase shift mask or grating pattern. The unmasked doped sections undergo a permanent change to a slightly higher refractive index after such exposure, resulting in an interlayer or a grating having two alternating different refractive indexes. This permits characteristic and useful partial reflection to then occur when a laser beam transmits through each interlayer. The reflected beam portions form a constructive interference pattern if the period of the exposed grating meets the condition:

$$2*\Lambda*n_{eff} = \lambda$$

where Λ is the grating spacing, n_{eff} is the effective index of refraction between the unchanged and the changed indexes, and λ is the laser light wavelength.

FIG. 2 (background art) shows the structure of a conventional fiber Bragg grating **1** according to the prior art. A grating region **2** includes an interlayer **3** having two periodically alternating different refractive indexes. As a laser beam **4** passes through the interlayer **3** partial reflection occurs, in the characteristic manner described above, forming a reflected beam **5** and a passed beam **6**. The reflected beam **5** thus produced will include a narrow range of wavelengths. For example, if the reflected beam **5** is that being worked with in an application, this separated narrow band of wavelengths may carry data which has been superimposed by modulation. The reflected beam **5** is stylistically shown in FIG. 2 as a plurality of parts with incidence angles purposely skewed to distinguish the reflected beam **5** from the laser beam **4**. Since the reflected beam **5** is merely directed back in the direction of the original laser beam **4**, additional structure is usually also needed to separate it for actual use.

Unfortunately, as already noted, conventional fiber Bragg gratings and the processes used to make them have a number of problems which it is desirable to overcome. For example, the fibers usually have to be exposed one-by-one, severely limiting mass-production. Specialized handling during manufacturing is generally necessary because the dosage of the UV exposure determines the quality of the grating produced. The orientation of the fiber is also critical, and best results are achieved when the fiber is oriented in exactly the same direction as the phase shift mask. The desired period of the Bragg grating will be deviated from if the fiber is not precisely aligned, and accomplishing this, in turn, introduces mechanical problems. Thus, merely the way that the fiber work piece is held during manufacturing may produce stresses that can cause birefringes to form in the fiber and reduce the efficiency of the end product grating.

Once in use, conventional fiber Bragg gratings may again require special handling. The thermal expansion coefficient of the base optical fiber is often significant enough that changing environmental conditions can cause the fiber to either expand or shrink to the extent that the period of the grating and its center wavelength shift.

From the preceding discussion of traditional and fiber Bragg gratings it can be appreciated that there is a need for optical gratings which are better suited to the growing range of grating applications. Two such applications are multiplexing and de-multiplexing. Fiber Bragg gratings have been widely used for these applications, despite the severe problems that come

with them. In particular, handling large numbers of light wavelengths and ranges of light wavelengths has been quite problematical with fiber Bragg gratings. Firstly, without complex additional structure, fiber gratings do not direct the light beams carrying multiplexed and especially demultiplexed wavelengths where they are usually desired. For example, the basic fiber Bragg grating merely reflects a separated wavelength back in the very same direction as the input beam from which it is being separated. Secondly, applying multiple wavelength handling characteristics and "chirping" to handle wavelength ranges in fiber gratings is difficult, with the difficulty increasing at a non-linear rate as additional wavelengths and ranges are provided for. Thirdly, as can be appreciated from the above discussion, constructing and maintaining assemblies of multiple traditional or fiber Bragg gratings to handle large numbers of wavelengths or ranges of wavelengths is also a task of non-linearly increasing difficulty.

Accordingly, new systems for multiplexing and de-multiplexing are needed. Such systems should preferably not rely on traditional or fiber Bragg gratings, and such systems should preferably be able to handle large numbers of light wavelengths and ranges of light wavelengths concurrently.

DISCLOSURE OF INVENTION

Accordingly, it is an object of the present invention to provide new systems for multiplexing and de-multiplexing.

Another object of the invention is to provide multiplexing and de-multiplexing systems having an ability to optionally handle large numbers of light wavelengths.

Another object of the invention is to provide multiplexing and de-multiplexing systems having an ability to optionally handle ranges of light wavelengths.

And another object of the invention is to optionally provide the above capabilities scalably.

Briefly, one preferred embodiment of the present invention is a multiplexing system. At least two light sources each provide an input light beams having a light wavelength, and a multi-dimensional grating receives the input light beams and diffracting at least one to form both into a single output light beam, thereby multiplexing the light wavelengths into the output light beam.

Briefly, another preferred embodiment of the present invention is a de-multiplexing system. A light source provides an input light beam having at least two light wavelengths, and a multi-dimensional grating receives the input light beam and diffracts at least one of the light wavelengths to form two output light beams, thereby de-multiplexing the light wavelengths into the respective output light beams.

An advantage of the present invention is that it provides new systems for both multiplexing and de-multiplexing, and such systems may concurrently handle multiple light wavelengths and ranges of light wavelengths.

Another advantage of the invention is that it characteristically physically separates the paths of the input and output light beams being multiplexed or de-multiplexed.

Another advantage of the invention is that it particularly well lends itself to constructing complex multiplexing and de-multiplexing systems, such as interleavers and de-interleavers.

Another advantage of the invention is that it may be constructed with stages which are physically discrete or contiguously physically integrated, and therefore provide embodiments which are readily usable in a variety of applications facilitated by flexibility.

Another advantage of the invention is that it may have uniform response characteristics, particularly in physically integrated embodiments. Stages within the invention may be

constructed in the very same substrate, and thus exhibit fixed operating relationships and environmental dynamics.

Another advantage of the invention is that embodiments are easily fabricated, using essentially conventional and well known materials and process, albeit not heretofore known or used in this art.

And another advantage of the invention is that it is highly economical, both in constructing and multiplexing and de-multiplexing systems and due to high reliability derived low maintenance in such systems.

These and other objects and advantages of the present invention will become clear to those skilled in the art in view of the description of the best presently known mode of carrying out the invention and the industrial applicability of the preferred embodiment as described herein and as illustrated in the several figures of the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The purposes and advantages of the present invention will be apparent from the following detailed description in conjunction with the appended figures of drawings in which:

FIG. 1a-b (background art) are cross sectional views of two traditional gratings, with depictions of light beams arriving incident to and being redirected by the gratings;

FIG. 2 (background art) is a cross sectional view of a conventional fiber Bragg grating, including a stylized depiction of a laser beam traveling through the grating;

FIG. 3 is a cross sectional view of a one-dimensional (1D) or linear Bragg grating, including a stylized depiction of a laser beam traveling through the grating;

FIG. 4a-p are a series of views at different stages of manufacture of one embodiment of a 1D Bragg grating, wherein:

FIG. 4a is a cross section side view of the Bragg grating as a substrate is prepared;

FIG. 4b is a cross section side view of the Bragg grating as a layer of photoresist is deposited;

FIG. 4c is a cross section side view of the Bragg grating as it is exposed under a pattern;

FIG. 4d is a top plan view of the Bragg grating after it is exposed;

FIG. 4e is a top plan view of the Bragg grating after a transmissive layer is deposited;

FIG. 4f is a cross section side view of the Bragg grating at the stage in FIG. 4e;

FIG. 4g is a top plan view of the Bragg grating after the exposed photoresist is removed;

FIG. 4h is a cross section side view of the Bragg grating at the stage in FIG. 4g;

FIG. 4i is a cross section side view of the Bragg grating after a new layer of photoresist is deposited;

FIG. 4j is a cross section side view of the Bragg grating as it is exposed under a pattern;

FIG. 4k is a top plan view of the Bragg grating after it is exposed;

FIG. 4l is a cross section side view of the Bragg grating after the exposed photoresist and portions of the layer below are removed;

FIG. 4m is a top plan view of the Bragg grating at the stage in FIG. 4l;

FIG. 4n is a cross section side view of the Bragg grating after a material having a different refractive index than the transmissive layer is deposited;

FIG. 4o is a cross section side view of the Bragg grating after excess material is removed;

and

FIG. 4p is a cross section side view of the Bragg grating after a new transmissive layer is deposited;

FIG. 5a-b are cross section side views depicting laser beams traveling through the finished Bragg grating of FIG.4a-p, wherein FIG. 5a shows how a beam will travel with minimum loss, and FIG. 5b shows how a beam will encounter constructive interference when the Bragg condition is met;

FIG. 6a-b are cross section side views at different stages of manufacture of a second embodiment of a Bragg grating, wherein FIG. 6a shows the grating after impurities are diffused into a substrate, and FIG. 6b shows the grating after a mask has been applied and additional impurities diffused into the substrate;

FIG. 7 is a flow chart summarizing a process for creating the Bragg grating;

FIG. 8 is a flow chart showing application of the process to create the embodiment of the Bragg grating of FIG. 3;

FIG. 9 is a flow chart showing application of the process to create the embodiment of the Bragg grating of FIG. 5a-b;

FIG. 10 is a flow chart showing application of the process to create the embodiment of the Bragg grating of FIG. 6a-b;

FIG. 11 is a schematic representation summarizing the structure and operation of a one-dimensional (1D) or linear grating, such as the Bragg gratings of FIG. 3-6b;

FIG. 12 is a perspective view showing that the principles of the linear grating of FIG. 11 can be extended to a 2D or planar grating;

FIG. 13 is a perspective view showing that the principles of the linear grating and the planar grating can be further extended to a 3D or cubical grating;

FIG. 14 is a schematic representation of surface-to-surface or intra-cell refraction effects in a grating;

FIG. 15 is a schematic representation of cell-to-cell interference between two vertically adjacent cells in a grating;

FIG. 16 is a schematic representation of cell-to-cell interference between two horizontally adjacent cells in a grating;

FIG. 17 is a schematic representation of general cell-to-cell interference, wherein a

grating contains three cells two in adjacent columns;

FIG. 18 is a schematic representation of the general case of FIG. 17 extended to operate in two dimensions, on two wavelengths, by using non symmetrical relationships in a generic grating;

FIG. 19 is a schematic representation of the non symmetrical generic grating of FIG. 18 as it might typically be applied in an actual planar or cubical grating according to the present invention;

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~~FIG. 20 is perspective view of a three-dimensional (3D) generic grating;~~

FIG. 21a-b include schematic overviews, wherein FIG. 21a is of a multiplexing system and FIG. 21b is of a de-multiplexing system according to the present invention;

FIG. 22 is a perspective view depicting how planar gratings may be combined to form a multiplexing device (a variation of the WDM device of FIG. 21);

FIG. 23 is a perspective view depicting how cubical gratings may also be combined to form a multiplexing device (another variation of the WDM device of FIG. 21);

FIG. 24 is a perspective view depicting how the multiplexing device of FIG. 22 can be an integrated unit;

FIG. 25 is a perspective view depicting how the multiplexing device of FIG. 23 can also be constructed as an integrated unit;

FIG. 26 is a perspective view depicting how planar gratings may also be combined to form a de-multiplexing device (a variation of the WDM device of FIG. 21);

FIG. 27 is a perspective view depicting how cubical gratings may similarly be combined to form a de-multiplexing device (another variation of the WDM device of FIG. 21);

FIG. 28 is a perspective view depicting how the de-multiplexing device of FIG. 26 can be an integrated unit by manufacturing the planar gratings as a single physical unit;

FIG. 29 is a perspective view depicting how the de-multiplexing device of FIG. 27 can also be constructed an integrated unit by manufacturing the cubical gratings as a single physical unit;

FIG. 30 is a perspective view depicting a de-interleaver, a sophisticated de-multiplexing system, according to the present invention;

FIG. 31 is a perspective view depicting how the de-interleaver of FIG. 30 may alternately be constructed as an integral unit;

FIG. 32 is a perspective view depicting an interleaver, a sophisticated multiplexing system, according to the present invention; and

FIG. 33 is a perspective view depicting how the interleaver of FIG. 32 may also alternately be constructed as an integral unit.

In the various figures of the drawings, like references are used to denote like or similar elements or steps.

BEST MODE FOR CARRYING OUT THE INVENTION

Preferred embodiments of the present invention are a wavelength division multiplexing (WDM) system and a wavelength division de-multiplexing (WDd-M) system. As illustrated in the various drawings herein, and particularly in the view of FIG. 21, the preferred embodiment of the WDM system is depicted by the general reference character 1000 and the preferred embodiment of the WDd-M system is depicted by the general reference character 1100.

FIG. 1-2 (background art) have already been discussed. As basic introduction, FIG. 3 depicts a one-dimensional (1D) or linear Bragg grating. FIG. 4a-p depict one embodiment of the 1D grating at various stages of fabrication and FIG. 5a-b depict operation of this 1D grating. FIG. 6a-b then depict another embodiment of the 1D Bragg grating at stages in fabrication. FIG. 7-10 summarize a suitable maufacturing process and variations thereof which may be used to produce the 1D gratings, or extended in straightforward manner to produce higher order gratings. FIG. 11 summarizes aspects of 1D gratings, and FIG. 12-20 present aspects of such higher order gratings, specifically of 2D or "planar" gratings and 3D or "cubical" gratings. Linear gratings and manufacturing techniques, generally, are the subject of the present inventors' co pending patent application 09/953,468, hereby incorporated by reference in its entirety. Planar and cubical gratings are the subject of the present inventors' co pending patent application titled "Multidimensional Optical Gratings" and also filed on Nov. 9, 2001, also hereby incorporated by reference in its entirety.

FIG. 3 is a cross sectional view depicting a one-dimensional (1D) or linear Bragg grating **100**, with a laser beam **102** stylistically represented as traveling through it. The Bragg grating **100** includes a substrate **104**, atop which the major operational elements have been constructed. The substrate **104** may be a material such as silicon wafer, glass plate, etc. A reflective layer **106** has been deposited atop the substrate **104**. Suitable materials for this include inherently reflective ones, such as metallic coatings like gold, silver, or aluminum, as well as materials having a low refractive index relative to the refractive indices of the materials in a grating region (described next).

A grating region **108** is provided atop the reflective layer **106**. Various materials and manufacturing techniques may be used to construct this grating region **108** and, in fact, a substantial part of the following discussion covers such variations. For purposes here, the grating

region **108** can be viewed simply as including an interlayer **110** of regions of a first transmissive material **112** and a second transmissive material **114**. The first transmissive material **112** and second transmissive material **114** have different refractive indices and are interspaced by one-quarter of the wavelength of light which the Bragg grating **100** will filter (or by an odd numbered multiple of one-quarter wavelength).

An over-fill layer **116** is provided atop the grating region **108**. It may be a material having a different refractive index, relative to the refractive indices of the other materials in the grating region **108**, it may be additional of the transmissive materials **112, 114** (as is shown here), or it may be a metallic coating similar to the reflective layer **106** used for similar purposes below the grating region **108**.

Operationally, the Bragg grating **100** receives the laser beam **102** in the manner shown in FIG. 3. [For simplified explanation, "laser beam" is used herein as a generic term to represent all suitable light beams. Although light from laser sources is today predominantly used in applications where the Bragg grating **100** will be widely employed, those skilled in the art will readily appreciate that light from other sources may be used as well.] The reflective layer **106** serves to reflect strayed portions of the laser beam **102** back in the original direction. Similarly, the over-fill layer **116** also does this. Here the over-fill layer **116** is of the same material as the second transmissive material **114** and it reflects the laser beam **102** because its index of refraction is substantially higher than that of the surrounding air.

As the laser beam **102** passes through the interlayer **110** of the grating region **108** it encounters the boundaries between the first and second transmissive materials **112, 114**. In particular, it encounters the respectively different refractive indices there. Partial reflection then occurs as the laser beam **102** passes through each boundary, forming a reflected beam **118** and a passed beam **120**. [The reflected beam **118** is stylistically shown in FIG. 3 as a plurality of parts with incidence angles purposely skewed to distinguish the reflected beam **118** from the laser beam **102**.] The reflected beam **118** will include a narrow range of wavelengths, formed in the characteristic manner of the Bragg condition by constructive interference in the light that is reflected, and the passed beam **120** includes the light of other wavelengths that were also present in the laser beam **102**.

FIG. 4a-p are a series of views at different stages of manufacture of one embodiment of the Bragg grating **100**. FIG. 4a is a side view of a substrate **202**. As already noted, the substrate

is of a suitable material upon which the major operational elements are constructed. At this initial stage the substrate **202** is essentially homogeneous. FIG. 4b is a side view after a photoresist layer **204** has been deposited atop the substrate **202**.

FIG. 4c is a side view as the Bragg grating **100** is exposed. A photomask **206** having a pre-designated pattern **208** is provided and the Bragg grating **100** is exposed through it to light **212** which is appropriate for causing a photochemical reaction in the photoresist layer **204**. This produces an unexposed region **204a** and an exposed region **204b**. FIG. 4d is a top view of the Bragg grating **100** after exposure, particularly depicting the unexposed region **204a** and the exposed region **204b**. Typically these would be termed to now have negative resist and positive resist, respectively.

FIG. 4e is a top view of the Bragg grating **100** after a transmissive layer **214** is deposited. As can be seen, some of the unexposed region **204a** and some of the exposed region **204b** of the photoresist layer **204** are left uncovered at this stage. FIG. 4f is a side view at this stage. The transmissive layer **214** has a thickness exceeding the height of light beams with which the Bragg grating **100** will later be used. In the inventors have found that SiO2 is particularly suitable for the transmissive layer **214**. This material is easily "worked" as needed and its refractive index, of nominally 1.52, is also good. Many other materials may also be used, however. Without limitation, other suitable candidates which are widely used industrially are Al2O3, with a refractive index of 1.63, and MgF2, with a refractive index of 1.38. [Still other candidates include amorphous silicon-hydrate (SiH, SiH2, SiH3, SiH4), B, P, ZnSe, ZnS, GaP, SrTiO3, Si, Ge, InSb, YSZ, AlAs, BaTiO3, BiSiO20, Bi12GeO20, AlN, BN, AgGaS2, LiTaO3, CuCaS2, TlI, TlCl, TlBr, AgCl, AgBr, AgI, AgGaSe2, KnbO3, and even some organic materials.]

The unexposed region **204a** remains once the exposed region **204b** is removed (via any of various conventional means, chemical etching, dry etch techniques, subliming by baking, etc.). FIG. 4g is a top plan view and FIG. 4h is a side view of the Bragg grating **100** after removal. As can particularly be seen in FIG. 4h, removing the exposed region **204b** leaves an air gap **216** between the substrate **202** and the transmissive layer **214**. [Note, the "air gap" here may ultimately contain any gas present in the environment surrounding the Bragg grating **100**. The inert gasses, N2, CO2, air, other gas mixtures, etc. are examples of gases commonly used in electronic equipment today. For that matter, the "air gap" can even be a vacuum. As will be seen in the operational discussion, below, the index of refraction of the air gap is what is key, and not

what fills it.]

FIG. 4i is a side view of the Bragg grating **100** after a new photoresist layer **218** has been deposited, and FIG. 4j is a side view as it is exposed. A photomask **220** having a grating pattern **222** is here provided and the Bragg grating **100** is exposed through it to light **224**. This produces an unexposed region **218a** and a plurality of exposed regions **218b**. FIG. 4k is a top view of the Bragg grating **100** after it is exposed in this manner, particularly showing the unexposed region **218a** and the exposed regions **218b**.

FIG. 4l is a side view of the Bragg grating **100** after the exposed regions **218b** of the photoresist layer **218** and portions of the transmissive layer **214** below it have been removed. In FIG. 4l the unexposed region **218a** is also shown as having already been removed. A key point to note, for this manufacturing variation, is that portions of the transmissive layer **214** are not removed so deeply that the air gap **216** is reached. The reason for this is provided in an operational discussion, below. FIG. 4m is a top view of the Bragg grating **100** at this stage. From FIG. 4l and FIG. 4m it can be appreciated that an array of open trenches now defines the grating region **226** in the transmissive layer **214**.

FIG. 4n is a side view of the Bragg grating **100** after an over-fill layer **228** is deposited into the array of trenches. The over-fill layer **228** is of a material having a slightly different refractive index than the transmissive layer **214**, and it fills in the openings grating region **226** so that a linearly extending interlayer array **230** is formed. The material of the over-fill layer **228** may be one of the same set of candidate materials for the transmissive layer **214**, e.g., Si, SiO2, Al2O3, MgF2, etc., but it will either be of a different such material or, if the same, it will be treated to achieve a different refractive index.

FIG. 4o is a side view of the Bragg grating after excess material from the over-fill layer **228** has been removed. One process suitable for this is polishing. The unexposed region **218a** was shown as having been already removed in FIG. 4l, but it could alternately have been left, the over-fill layer **228** applied atop it, and then it and the excess from the over-fill layer **228** removed together. In some manufacturing scenarios this is a matter of mere choice, but in others there may be an incentive to remove the over-fill layer **228** earlier. For instance, in common semiconductor fabrication processes organic photoresist materials are used. These are generally suitable for use here as well, but with early removal desirable to avoid contaminating the over-fill layer **228** as it is later applied.

Finally, FIG. 4p is a side view of the Bragg grating **100** after a new transmissive layer **232** is deposited. In this embodiment the inventors prefer that the transmissive layer **214** and the transmissive layer **232** have the same refractive index, and thus that they be of the same material. This is not a requirement, however. The transmissive layer **232** may, for instance, be of the same material and have the same refractive index as the over-fill layer **228**. As will become more clear in the discussion below, it is desirable that the over-fill layer **228** have a refractive index substantially different than that of air (refractive index = 1). Thus a material like, say, MgF2 with a refractive index of 1.38, may be quite suitable for use in the over-fill layer **228** but not in the transmissive layer **232**. This completes construction of the Bragg grating **100**.

FIG. 5a-b are cross section side views depicting a light beam **240** traveling through the finished Bragg grating **100** of FIG. 4a-p. In FIG. 5a the light beam **240** has strayed portions **242**, some of which go upward and others of which go downward. The downward traveling of the strayed portions **242** encounter an interface **244** at the juncture of the transmissive layer **214** and the air gap **216**, and are reflected back into the transmissive layer **214**. Similarly, the upward traveling of the strayed portions **242** encounter an interface **246** at the juncture of the transmissive layer **232** and the air above the Bragg grating **100**, and are reflected back into the transmissive layer **232**. Thus the interface **244** created at the air gap **216**, and the disparity between the refractive indices, is used to achieve reflection. This is structurally different than the embodiment of FIG. 3, where the reflective layer **106** was deposited below the grating region **108**, but it is functionally equivalent. The light beam **240** is thus here also able to travel through the Bragg grating **100** with minimum power loss.

FIG. 5b shows how the main portion of the light beam **240** encounters the interlayer array **230** in the grating region **226**, how a reflected portion **248** (stylistically shown here also as a plurality of parts with purposely skewed incidence angles) is created, and how a passed portion **250** is passed. The reflected portion **248** will include a narrow range of wavelengths, formed by constructive interference, and the passed portion **250** will include the light of other wavelengths that are also present in the light beam **240**.

FIG. 6a-b are side views at different stages of manufacture of a second embodiment of a Bragg grating **100**. FIG. 6a shows the Bragg grating **100** in an early stage of manufacture, after a substrate **302** has had impurities diffused into a grating region **304**. FIG. 6b shows the Bragg grating **100** in a later stage of manufacture, after a mask **306** having a suitable open grating

pattern **308** has been applied and additional impurities have been diffused into the grating region **304** below the openings in the grating pattern **308** to form a linearly extending interlayer array **310**. The Bragg grating **100** here can then be finished, in straightforward manner, by removing the mask **306** and applying an over-fill layer (not shown).

This approach employs the fact that the refractive indices for certain materials will change when impurities are diffused into them. One well known example is silicon: the refractive index for pure silicon is 3.5 but reduces to as low as 2.1 when a heavy dosage of hydrogen is diffused into it. The refractive index can further be reduced to even lower than 1.5 by incorporating different levels of oxygen. Another example material is silica ($SiO2$): when it's diffused with germanium and under exposure of UV light its refractive index increases slightly. The Bragg grating **100** depicted in FIG. 6a-b can thus take advantage of these properties to obtain the desired characteristics in the interlayer array **310**.

FIG. 7 is a flow chart summarizing a process **400** for creating the Bragg grating **100**. The process **400** starts in a step **402**, where basic and conventional set up operations can be performed, as needed and as desired.

In a step **404** a substrate is provided and prepared. This serves as the basis of a workpiece for the rest of the process **400** and for construction of the Bragg grating **100**.

In a step **406** a lower reflective means is constructed.

In a step **408** a grating region having an interlayer is constructed.

In a step **410** an upper reflective means is constructed.

Finally, in a step **412** the process **400** ends. This is where basic and conventional wrap up operations can be performed, as needed and as desired. The process **400**, which in deed has been described very generally, is now finished.

FIG. 8 is a flow chart showing application of the process **400** to create the Bragg grating **100** of FIG. 3. The conventional or straightforward step **402** (start) and step **404** (substrate preparation) again occur. The step **406** (constructing a lower reflective means) here includes a single sub-step **422** for providing a reflective layer, such as a metallic coating, onto the (substrate) workpiece.

The step **408** (constructing the grating region and interlayer) here includes a number of sub-steps. The first of these is a sub-step **424** to provide a first transmissive layer on the workpiece, atop the reflective layer. In a sub-step **426** a first photoresist layer is then provided on

the workpiece, atop the first transmissive layer. In a sub-step **428** the workpiece is exposed under a photomask. The photomask particularly has a pattern as already described, e.g., for a simple Bragg grating a pattern interspaced by one-quarter of the wavelength (or by an odd numbered multiple of that) of the light which will be filtered.

In a sub-step **430** the exposed portions of the first photoresist layer are removed. Underlying portions of the first transmissive layer are also removed to a desired depth.

In a sub-step **432** a second transmissive layer is applied to the workpiece, atop the unetched portions of the first photoresist layer and filling in the first transmissive layer. The second transmissive layer particularly has a different index of refraction than the first transmissive layer.

In a sub-step **434** excess material, that is the upper most material here, is removed from the workpiece. Specifically, the second transmissive layer and unetched portions of the first photoresist layer are removed to a depth at least flush with the top most portions of the first transmissive layer. This completes the step **408** (grating region and interlayer construction).

The step **410** (constructing the upper reflective means) here includes a single sub-step **436** for providing a third transmissive layer on the workpiece, atop the remaining first and second transmissive layer portions. This third transmissive layer has the same index of refraction as the first or second transmissive layer. In a final step **412** the process **400** is now finished.

FIG. 9 is a flow chart showing application of the process **400** to create the Bragg grating **100** of FIG. 5a-b. The conventional or straightforward step **402** (start) and step **404** (substrate preparation) again occur.

The step **406** (constructing a lower reflective means) here includes a number of sub-steps. The first of these is a sub-step **438** to provide a first photoresist layer on the (substrate) workpiece. In a sub-step **440** the workpiece is exposed under a first photomask. In a sub-step **442** a first transmissive layer is provided on the workpiece, atop the first photoresist layer. In a sub-step **444** the exposed portion of the first photoresist layer is removed, leaving an air gap between the substrate and the first transmissive layer.

The step **408** (constructing the grating region and interlayer) here also includes a number of sub-steps. In fact, in this variation on the process **400** the sub-steps **442**, **444** are part of both step **406** and step **408**. The rest of the step **408** continues with a sub-step **446** where a second photoresist layer is applied to the workpiece, atop the first transmissive layer. In a sub-step **448**

the workpiece is exposed under a second photomask having a suitable pattern.

In a sub-step **450** the exposed portions of the second photoresist layer and the underlying first transmissive layer are removed to a desired depth. This leaves an array of openings or trenches.

In a sub-step **452** a second transmissive layer is applied to the workpiece, atop the unetched portions of the second photoresist layer and filling in the trench array in the first transmissive layer. This second transmissive layer has a different index of refraction than the first transmissive layer.

In a sub-step **454** the upper most material, specifically the second transmissive layer and unetched portions of the second photoresist layer, is removed to a depth at least flush with the top most portions of the first transmissive layer. This completes the step **408** (grating region and interlayer construction).

The step **410** (constructing the upper reflective means) here includes the single sub-step **436** for providing a third transmissive layer on the workpiece, atop the remaining first and second transmissive layer portions. This can be essentially the same as the step **410** and sub-step **436** of FIG. 8. In a final step **412** the process **400** is now finished.

FIG. 10 is a flow chart showing application of the process **400** to create the Bragg grating **100** of FIG. 6a-b. The conventional or straightforward step **402** (start) and step **404** (substrate preparation) again occur.

The step **406** (constructing a lower reflective means) here may be viewed as a variation of the approach used for step **410** in FIG. 8 and FIG. 9, or as a variation of the approach used for step **406** FIG. 9. A lower reflector is formed by the interface of the material of the substrate with air or another material below the substrate. As discussed, below, the grating region need not extend all the way down and through the substrate, and the excess material in the substrate thus can serve as part of the lower reflector. In this regard, step **404** and step **406** are essentially merged. Alternately, a reflective material can be applied, similar to the reflective coating used in sub-step **422** in FIG. 8.

The step **408** (constructing the grating region and interlayer) here includes a number of sub-steps. The first of these is a sub-step **456** to dope a portion of the substrate (or a first transmissive layer atop a substrate) which will ultimately become the grating region with an impurity. In a sub-step **458** a mask is constructed on the workpiece, atop the grating region. In a

sub-step **460** an additional or other impurity is doped into the non-masked portions of the grating region. In a sub-step **462** the mask is removed.

The step **410** (constructing the upper reflective means) here may include the approach shown in FIG. 8 for step **406**, using sub-step **422**, or it may include the approach shown in FIG. 8 and FIG. 9 for step **408**, using sub-step **436**. Finally, in a step **412** the process **400** is finished. It is, however, a straightforward extension of the process **400** to use multiple iterations of the various steps, to construct the sophisticated variations on the Bragg grating **100** which are now described.

With reference back to the earlier figures, more than two transmissive materials can be placed into the path a light beam will encounter. In FIG. 5b two materials having two indices of refraction are present in the transmissive layer **214** and in the interlayer array **230**. In FIG. 6b, the substrate **302** is one material having one index of refraction, and the interlayer array **310** is effectively of two other materials (after it is doped or has impurity diffused into it). Even variations on the Bragg grating **100** like those in FIG. 3, FIG. 5a-b, and FIG. 6a-b are relatively simple, and the true scope of the invention is much broader. It is a straightforward extension of the process **400** to use multiple materials (actual different materials or effectively so by treatment to change the indices of refraction). One reason to do this is to handle multiple frequencies in a light beam, or to broaden the bandwidth of the frequencies filtered. Similarly, the spacing of the regions in the interlayers **110**, **230**, **310** can be changed to do this, much in the manner of periodically "chirped" prior art Bragg gratings.

One sophisticated manufacturing technique which may be used is to tune the indices of refraction. For instance, amorphous silicon-hydrate (SiH, SiH2, SiH3, SiH4) can be "tuned" by temperature. This can be used to obtain specific desired indices of refraction, or to apply a gradient in the indices in one or more materials. In this manner, the index of refraction is another factor which can be controlled during grating fabrication to achieve chirped or other sophisticated grating types.

FIG. 11 is used next to summarize the one-dimensional (1D) or linear grating. FIG. 12 and 13 then help in an introduction illustrating that the principles of the one-dimensional (1D) or linear grating can be extended to provide a two-dimensional (2D), planar grating, and also a three-dimensional (3D), cubical grating. FIG. 14-17 support derivations extending the principles to the multidimensional, 2D and 3D cases. And FIG. 18-20 depict how gratings having multiple

dimensions may have different optical properties relative to each such dimension.

FIG. 11 depicts the structure and operation of a 1D or linear grating **500** (e.g., any of the variations of the Bragg grating **100** already discussed). The linear grating **500** is made of at least two different transparent materials. One of these serves as a background material **502** and one or more others are interlayer materials, with multiple regions of one interlayer material **504** represented here.

The diffraction efficiency in the linear grating **500** depends on the effective refractive index of the particular interlayer material **504** and the background material **502**. The simplest case is depicted in FIG. 11, where just two materials are employed having refractive indices of n_1 and n_2. The background material **502** can have either n_1 or n_2, depending on manufacturing convenience, and here it has arbitrarily been made n_1.

The regions of the interlayer material **504** (n_2) are provided with a thickness **506** such that the phase difference between the reflecting portions of a light beam from both surfaces of a region are multiples of 360 degrees. This insures that constructive interference for a specific wavelength can occur. A similar rational, achieving constructive interference, applies to providing a separation **508** between the regions of the interlayer material **504**.

In operation, a light beam **510** may be directed into the linear grating **500**, as shown in FIG. 11, to form a reflected beam **512** (shown here skewed for emphasis) and a passed beam **514**. The reflected beam **512** will contain the light of the specific wavelength for which constructive interference occurs, and the passed beam **514** will contain all other wavelengths. Thus, the linear grating **500** can be used as a filter to obtain light of high wavelength purity. Alternately, in the manner of prior art gratings, the thicknesses **506** and the separations **508** of the regions of the interlayer material **504** may be varied to "chirp" the linear grating **500** and thereby broaden the reflected beam **512** to include a range of wavelengths.

FIG. 12 is a stylized perspective view showing that the principles of the linear grating **500** of FIG. 11 can be extended to a 2D or planar grating **600**. The planar grating **600** has a background **602** containing a grid of cells **604**. The background **602** has a refractive index, say, n_1, and the cells **604** have at least one different refractive index. For simplicity in this discussion, the cells **604** are all of the same material and refractive index, say, n_2.

In FIG. 12 an XYZ-axes icon **606** shows a standard Cartesian reference scheme used to facilitate this discussion. The cells **604** have a respective thickness **608** and separation **610** along

the X-axis, and also a respective thickness **612** and separation **614** along the Y-axis. These can be chosen in much the same manner as the thickness **506** and the separation **508** of the linear grating **500**. Furthermore, if desired, the respective sets of these may be chosen to be different, to obtain constructive interference for different specific wavelengths (discussed in more detail, presently).

FIG. 12 also includes stylized representations of a light beam **616**, a diffracted beam **618**, and a passed beam **620**, to depict how the planar grating **600** employs constructive interference in the XY-plane. The light beam **616** may contain a number of light wavelengths, including one which meets the Bragg condition for the thicknesses **608**, **612**, separations **610**, **614**, and refractive indices here. The diffracted beam **618** will then contain only light of the wavelength meeting the Bragg condition provided for, while the passed beam **620** will contain the other wavelengths present.

FIG. 13 is a stylized perspective view showing that the principles of the linear grating **500** and the planar grating **600** can be further extended to a 3D or cubical grating **700**. The cubical grating **700** has a background **702** containing a grid of cells **704**. The background **702** has a particular refractive index and the cells **704** have one or more other refractive indices. For simplicity, the cells **704** here are all of the same material.

In FIG. 13 an XYZ-axes icon **706** shows a standard Cartesian reference scheme used to facilitate this discussion. The cells **704** have respective thicknesses along the X-axis, Y-axis, and Z-axis, and also respective separations along each of these axes. If desired, these respective dimension sets may also be chosen to be different, to obtain constructive interference for different specific wavelengths. That is the case here and two of the three possible sets of thicknesses and separations have been chosen to be different.

FIG. 13 also includes stylized representations of a light beam **708**, a first diffracted beam **710**, a second diffracted beam **712**, and a passed beam **714**. The cubical grating **700** here employs one condition of constructive interference in the XY-plane as well as a second condition of constructive interference in the ZX-plane. The light beam **708** may contain a number of light wavelengths, including two which meet the respective Bragg conditions designed for here. The first diffracted beam **710** will thus contain the light wavelength subject to diffraction in the XY-plane, the second diffracted beam **712** will thus contain the light wavelength subject to diffraction in the YZ-plane, and the passed beam **714** will contain the other wavelengths. This is

now explained in further detail in a coverage of the principles underlying the inventive planar grating **600** and the inventive cubical grating **700**.

Turning now to derivations of how the principles in one dimension extend to multiple dimensions, FIG. 14 illustrates cell interference (based on intra-cell refraction) in a generic grating **800**. A background **802** is provided having a refractive index n_1, and is shown here with a single cell **804** (potentially one of many which may be present in embodiments of planar or cubical gratings according to the present invention). The cell **804** is of a material having a different refractive index, n_2, and it has a thickness **806** (d).

When a light beam **808** (carrying a wavelength λ) travels through the background **802** (medium n_1) and shines on a first surface **810** of the cell **804** at an incidence angle θ_1, a first reflected portion **812** (of the light beam **808**) is produced and reflected from the cell **804**, as shown. Concurrently, as similarly occurs in the linear grating, the rest of the light beam **808** transmits into the cell **804** (medium n_2) as a first refracted portion **814**. This first refracted portion **814** is refracted at the first surface **810** according to the law of refraction, or Snell's law:

$$n_1 * \sin\theta_1 = n_2 * \sin\theta_2,$$

where θ_2 is the refracted angle in the cell **804**. The first refracted portion **814** then travels through the cell **804** until it encounters a second surface **816** of the cell **804**, where part of it is reflected as a second reflected portion **818** and the rest exits the cell **804** as a transmitted portion **820**.

The second reflected portion **818** travels back to the first surface **810**, where it is refracted back into the background **802** as a second refracted portion **822**. This second refracted portion **822** constructively interferes with the first reflected portion **812** if the thickness **806** (d) and the refracted angle θ_2 satisfy the condition (based on Bragg's law):

Eq. 1: $$2 * n_2 * d * \cos\theta_2 = k * \lambda,$$

where k is an integer.

The transmitted portion **820** simply exits the cell **804** and continues to propagate in the original direction of the light beam **808**, potentially to encounter and interact with another cell, and repeat the phenomenon.

It follows that by design with proper values for n_1, n_2, d, and the incidence angle θ_1, that portions of the light beam **808** can be made to constructively interfere and, in a grating constructed accordingly, the cells will behave like scatterers, to scatter light beams in a designated direction.

On the other hand, there also exists the possibility of cell-to-cell interference. In order to employ this to also achieve constructive interference between adjacent cells, certain conditions also have to be met. FIG. 15 depicts cell-to-cell interference between two vertically adjacent cells, and FIG. 16 depicts cell-to-cell interference between two horizontally adjacent cells.

Turning first to FIG. 15, it depicts the generic grating **800**, again, with the background **802**, but now containing a lattice of two of the cells **804** which are vertically aligned. The reflected intensity will be maximum if the optical path difference (OPD_v) between the cells **804** meets the condition:

$$OPD_v = 2*\delta_1 = 2*n_1*b*\cos\theta_1 = m*\lambda,$$

where δ_1 is the distance shown, b is a vertical separation **826** between the two adjacent cells, and m is an integer.

Turning next to FIG. 16, it similarly depicts the generic grating **800**, only now with the background **802** containing a lattice of two of the cells **804** which are horizontally aligned. The reflected intensity here will be maximum if the optical path difference (OPD_h) between the cells **804** meets the condition:

$$OPD_h = \delta_1 - \delta_2 = 2*n_1*a*\sin\theta_1 = l*\lambda,$$

where δ_1 and δ_2 are the distances shown, a is a horizontal separation **828** between the two adjacent cells, and l is an integer.

FIG. 17 depicts a general case for cell-to-cell interference, wherein the generic grating **800** now contains three cells **804**, in adjacent columns. The reflected intensity will be maximum if the optical path difference (OPD) between these cells **804** meets the condition:

$$\text{Eq. 2:} \qquad OPD = \delta_1 - \delta_2 = 2*n_1*(a^2+c^2)^{1/2}*\cos(\phi-\theta_1) = m*\lambda,$$

where δ_1 and δ_2 are the distances shown, a is the horizontal separation **828** between two adjacent cells, b is the vertical separation **826** between the two adjacent cells, c = is a vertical separation **830** between two cells in adjacent columns, ϕ is the angle shown (essentially, a measure of cell-to-cell dis-alignment relative to the incidence surfaces), θ_1 is the angle of light beam incidence, and m is an integer.

FIG. 18 depicts the general case of FIG. 17 extended to operate two dimensionally, on two wavelengths by using non symmetrical relationships in a grating **850**. A background **852** (having refractive index n_1) here contains three cells **854** (having refractive index n_2). The cells **854** have a horizontal thickness **856** (x), a vertical thickness **858** (y), a horizontal separation **860**

(a), a first vertical separation **862** (e), and a second vertical separation **864** (f). A light beam, stylistically represented as first portions **866** having a first wavelength λ_1 and second portions **868** having a second wavelength λ_2, approaches the cells **854**. The first portions **866** are then scattered as shown if Eq. 2 is satisfied with respect to θ_1. Similarly, the second portions **868**) are scattered as shown if Eq. 2 is satisfied with respect to θ_2.

FIG. 19 is a diagram of the grating **850** of FIG. 18 as it might typically be applied in an actual planar or cubical grating according to the present invention. Since the "pitch" of each grating cell-surface determines a "resonance" wavelength, by varying the pitch and the cell spacing in a two-dimensional grating an incoming multiple-wavelength laser beam can be sorted into single-wavelength beams in a spatial domain. Since the parameters of each individual grating unit can be made accurately with semiconductor-like manufacturing process, the directions of each single-wavelength laser beam can be made parallel, for use in ultimate applications.

FIG. 20 is perspective view of a three-dimensional (3D) grating **880**. In the grating **880** a background material (not shown, but of a material having refractive index n_1) contains non symmetrical cubic cells **882** (of a material having refractive index n_2). An incoming light beam including three wavelengths λ_1, λ_2, λ_3, stylistically represented as first portions **884**, second portions **886**, and third portions **888**, is incident to the cells **882** on their surfaces. With respect to each of the three different incident surfaces and opposed surface sets, the cells **882** each behave like a "scatterer" according to Eq. 1 and 2, above.

Firstly, with respect to Eq. 1, the light wavelengths are each respectively scattered by a different set of opposite surfaces if:

$$2*n_2*d_i*\cos\theta_i = m_i*\lambda_i,$$

where d_i is the respective cell thickness perpendicular to the "scattering" surface, θ_i is the respective refracted angle inside the cell, and m_i is an integer respectively in each dimension. In fact, λ_i can be viewed as the "inter-cell resonant wavelength" for opposite cell surfaces optically separated by d_i.

Secondly, with respect to Eq. 2, the light wavelengths are each respectively scattered by a different incident surface if:

$$OPD_i = 2*n_1*a_i*\cos(\phi_i-\theta_i) = m_i*\lambda_i,$$

where OPD_i is the optical path difference between the cell-to-cell incident surfaces, a_i is the cell-

to-cell separation, ϕ_i is the angle of cell-to-cell dis-alignment (relative to the incidence surfaces), θ_i is the angle of light beam incidence to the incidence surfaces, and m_i is an integer.

There are a number of factors which provide the present invention with its novel abilities. For constructing the invention, these may be tailored individually or collectively, and the following, without limitation, now discusses of some of these factors.

The background material's index of refraction (n_1) can be considered by itself. While many embodiments will intentionally keep this constant throughout the grating, it can also be controlled to craft sophisticated embodiments of the invention. Using micro-fabrication techniques it is a simple matter to make different regions of the background material have different indices of refraction. Conceptually, this is can be viewed as constructing a number of contiguous gratings. It is useful to work with multiple light wavelengths in the gratings. More complex micro-fabrication techniques, however, also permit making all, or one or more parts, of the background material have indices of refraction which vary. For instance, a gradient can be imposed by controlled doping during grating fabrication. This permits constructing gratings that work with a range of light wavelengths (somewhat analogous in effect to conventional chirped gratings).

~~In multi-dimensional contexts such a gradient need not extend merely in a single-dimensional, lengthwise manner, like the light beam **510** progressing through the linear grating **500** in FIG. 11. For example, if the index of refraction were varied from, say, the top-left corner to the bottom-right corner in the linear grating **850** in FIG. 19, the first portions **868** (λ_1) and the second portions **868** (λ_2) would both contain broadened wavelength response (i.e., each be "chirped"). Similarly, if the index of refraction were varied from corner to corner in the cubical grating **880** of FIG. 20, the three respective portions **884**, **886**, **888** (λ_1, λ_2, λ_3) there would each be wavelength broadened.~~

Next the cell material's index of refraction (n_2) can be considered by itself. Again, sophisticated embodiments of the invention can be constructed by working with the index of the material here. Constructing the cells using different single-index materials permits making gratings that work with multiple light wavelengths. Here that capability can be also particularly well integrated into the grating as a whole. FIG. 12 and the planar grating **600** depicted there can help illustrate this. The right-most cells **604** might have index n_{2a}, the middle-most cells have a different index n_{2b}, the left-most cells again have index n_{2a}, (and so forth in the many, many

"layers" in most practical embodiments). The diffracted beam **618** will then contain two wavelengths, (λ_a, λ_b). Alternately, the cells **604** by index (n_{2a}, n_{2b}) can be arranged other than by layers. They can even be placed randomly. The ratio of cells **604** having index n_{2a} to those having index n_{2b} can also be varied, to "strongly" separate one wavelength (say, λ_a) and less completely extract the other (λ_b). Of course, the invention is not limited to just cells having two indices (n_{2a}, n_{2b}); a third (n_{2c}), fourth (n_{2d}), etc. are possible as well. Similarly, once the concept is grasped for two-dimensions, it follows that it can be also be employed in three (consider FIG. 13 and the cubical grating **700** there).

Constructing the cells using internally varying material indices is also possible. This is another way to construct gratings that work with ranges of light wavelengths (again, somewhat analogous in effect to conventional chirped gratings, but here potentially with respect to each grating-dimension).

Next consider the background and cell material's indices of refraction together (n_1 and n_2). These two indices may be viewed as one factor, an "effective index" or "relative index" that effects the overall efficiency of the grating. Additionally, these indices can be worked with to facilitate construction. If one material (say, n_2) is hard to hold constant or to vary the characteristics of during grating fabrication, the other (n_1) can be worked with instead. It should also be noted that $n_1 < n_2$ or $n_1 > n_2$ can be used.

The surface-to-surface dimensions of the cells can also be considered. If the cells are made very small, comparable to the wavelength of the light source. Then the surface-to-surface dimensions are not a factor and Bragg's law can apply directly. Alternately, as has been shown above, the cells can be made larger. In this case, Bragg's law can still apply if one or more cell "thickness" is made so that the reflected waves constructively interfere.

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As shown in FIG. 14, 18, and 20, the cells can have one, two, or even three different thickness, to effect a corresponding number of light wavelengths differently. Furthermore, in sophisticated embodiments these respective cell thickness can intentionally be different. To help appreciate this further, reconsider the above discussion about varying cell index of refraction. Cell to cell variation can be employed. Finite sets or ranges of thicknesses for the different cells can be used; the cells so constructed can be placed in layers, another ordering, or randomly; and the proportions between the different cells can cells equal or otherwise, to purposely work more or less strongly with particular light wavelengths.

The cell-to-cell spacings can likewise be considered. As shown in FIG. 15, the row-to-row placement of the cells can be controlled (to achieve uniformity or intentional forms of "non-uniformity," like the examples noted above). Similarly, as shown in FIG. 16, the column-to-column placement of the cells can be controlled (again for uniformity or intentional non-uniformity). Furthermore, however, as shown in FIG. 17, the cell-to-cell placement can be asymmetric. Either row-to-row asymmetry, column-to-column asymmetry, or both can be used. Still further, although semantically somewhat an oxymoron, this asymmetry can be uniform or non-uniform. For example, any or all of the separations **826**, **828**, **830** can be held constant or varied.

The cell quantity present is also a factor meriting consideration. If a large grating with may cells is cut into slices, Bragg's law holds for each. If only two rows, columns, etc. of cells are involved, the transition from constructive to destructive interference is quite gradual. In contrast, if many cells are present, the constructive interference will peak very sharply, with mostly destructive interference in between the peak wavelengths. In fact, this sharpening of the peaks is very similar to the sharpening of diffraction peaks from a diffraction grating as the number of slits increases. Of course, cutting large gratings to produce multiple smaller ones also has obvious manufacturing utility.

It should be noted that the examples in the figures herein, so far, have shown single gratings with no external components. In use there will, of course, be conventional external components such as a laser light source, and typically much more. Furthermore, in suitable applications considerable benefit can be obtained by using multiple gratings and other components together. One of the particular strengths of micro fabrication type processes, as used by the present invention, is that they can be used to construct large numbers and varieties of components concurrently. Such products can then be used either in operational combination or separately. Thus, for example, multiple linear gratings **500**, planar gratings **600**, or cubical gratings **700** can be constructed together in a linear or other operational arrangement, using different lattice dimensions, doping, etc. to work with different light wavelengths. If desired, other electrical and micro-mechanical components can also be constructed in the same substrate or in the same layer materials, e.g., one or more electro-optical sensors or micro mirrors. The present invention is thus very highly integrateable with IC and MEMS technology.

FIG. 21a-b include schematic overviews of a multiplexing system **1000** and a de-

multiplexing system **1100**, according to the present invention. Turning first to FIG. 21a, it depicts the multiplexing system **1000** including a plurality of light sources **1002** which each respectively provide a light beam **1004** having a wavelength (or wavelength range) of interest ($\lambda_{1\text{-}8}$). Some examples of such light sources **1002**, without limitation, include local instances of laser diodes (emitting) or optical fibers delivering light from remote other sources. The multiplexing system **1000** further includes a WDM device **1006** able to combine the light beams **1004** into a single light beam **1008** having all of the wavelengths ($\lambda_{1\text{-}8}$). The multiplexing system **1000** lastly includes a light target **1010**. Some potential examples of this might be a local laser diode (detecting) or an optical fiber to deliver the light beam **1008** to some remote point for use there.

In contrast, FIG. 21b depicts the de-multiplexing system **1100** including a single light source **1102** which provides a light beam **1104** having multiple wavelengths of interest ($\lambda_{1\text{-}8}$). Possible examples of such a light source **1102** include local laser diodes (emitting), with appropriate light combining optics, or an optical fiber delivering such light from a remote other source. The de-multiplexing system **1100** further includes a WDM device **1106** which is able to separate the light beam **1104** into respective single light beams **1108** each having one of the wavelengths (or wavelength ranges)($\lambda_{1\text{-}8}$). The de-multiplexing system **1100** lastly includes a plurality of light targets **1110**. Examples of these include local laser diodes (detecting) or optical fibers to deliver the light beams **1108** to one or more remote points for use there.

The light sources **1002**, **1102** and the light targets **1010**, **1110** may be essentially conventional. Furthermore, the WDM devices **1006**, **1106** may be the same device, just applied differently. However, as is next described, the WDM devices **1006**, **1106** may have a number of internal variations.

FIG. 22 is a perspective view depicting how planar gratings, as discussed elsewhere herein, may be combined to form a multiplexing device **1200** (i.e., a variation of the WDM device **1006** of FIG. 21a). A first planar grating **1202**, a second planar grating **1204**, and a third planar grating **1206** are provided as shown (the cells therein are stylistically represented, and typically will not be oriented and spaced along the xyz-axes).

A first input beam **1208**, a second input beam **1210**, a third input beam **1212**, and a fourth input beam **1214** are provided and may enter the multiplexing device **1200**, as shown. The wavelength (λ_1) of the first input beam **1208** is such that it is not diffracted by any of the planar

gratings **1202, 1204, 1206** (or it may even be any light, as discussed below). The wavelength (λ_2) of the second input beam **1210** is such that it is diffracted by the first planar grating **1202,** but not by any of the other planar gratings **1204, 1206**. The wavelength (λ_3) of the third input beam **1212** is such that it is diffracted by the second planar grating **1204,** but not by the third planar grating **1206.** And the wavelength (λ_4) of the fourth input beam **1214** is such that it is diffracted by the third planar grating **1206.**

The first input beam **1208** and the second input beam **1210** enter the first planar grating **1202,** where, in the manner discussed elsewhere herein, they combine to from a first output beam **1216** having two wavelengths (λ_{1-2}). This first output beam **1216** and the third input beam **1212** then enter the second planar grating **1204,** where they similarly combine to from a second output beam **1218** having three wavelengths (λ_{1-3}). This second output beam **1218** and the fourth input beam **1214** then enter the third planar grating **1206,** where they likewise combine to form a final, third output beam **1220** having all four wavelengths (λ_{1-4}).

FIG. 23 is a perspective view depicting how cubical gratings, as discussed elsewhere herein, may also be combined to form a multiplexing device **1300** (i.e., another variation of the WDM device **1006** of FIG. 21a). A first cubical grating **1302,** a second cubical grating **1304,** and a third cubical grating **1306** are provided as shown (the cells here as well are stylistically represented, and typically will not be oriented and spaced along the xyz-axes).

A first input beam **1308,** a second input beam **1310,** a third input beam **1312,** a fourth input beam **1314,** a fifth input beam **1316,** a sixth input beam **1318,** and a seventh input beam **1320** are provided and may enter the multiplexing device **1300,** as shown. The wavelength (λ_1) of the first input beam **1308** is such that it is not diffracted by any of the cubical gratings **1302, 1304, 1306** (or it may even be any light, as discussed below). The wavelengths (λ_2, λ_3) of the second input beam **1310** and the third input beam **1312** are such that they are respectively both diffracted by the first cubical grating **1302,** but not by any of the other cubical gratings **1304, 1306.** The wavelengths (λ_4, λ_5) of the fourth input beam **1314** and the fifth input beam **1316** are such that they are respectively both diffracted by the second cubical grating **1304,** but not by the third cubical grating **1306.** And the wavelengths (λ_6, λ_7) of the sixth input beam **1318** and the seventh input beam **1320** are such that they are diffracted by the third cubical grating **1306.**

Thus, when the first input beam **1308,** the second input beam **1310,** and the third input beam **1312,** enter the first cubical grating **1302** they combine, in the manner discussed elsewhere

herein, to from a first output beam **1322** having three wavelengths (λ_{1-3}). This first output beam **1322**, the fourth input beam **1314**, and the fifth input beam **1316** then enter the second cubical grating **1304**, where they similarly combine to from a second output beam **1324** having five wavelengths (λ_{1-5}). This second output beam **1324**, the sixth input beam **1318**, and the seventh input beam **1320** then enter the third cubical grating **1306**, where they likewise combine to from a final, third output beam **1326** having all seven wavelengths (λ_{1-7}).

FIG. 24 is a perspective view depicting how the multiplexing device **1200** can be an integrated unit. The planar gratings **1202, 1204, 1206** can simply be manufactured as a single physical unit. The "intermediate" output beams **1216, 1218** are not shown here, but they will still effectively exist inside the integrated multiplexing device **1200** here. Similarly, FIG. 25 is a perspective view depicting how the multiplexing device **1300** can also be constructed an integrated unit.

The multiplexing devices **1200, 1300** in FIG. 22-25 have a number of similarities. For example, the gratings **1202, 1204, 1206, 1302, 1304, 1306** can be viewed as stages, and there is no reason that fewer or additional such stages cannot be used. The input beams **1208, 1210, 1212, 1214, 1308, 1310, 1312, 1314, 1316, 1318, 1320** may be fixed, and the gratings manufactured to accommodate the wavelengths present in the input beams, or vice versa. Combinations of planar and cubical gratings are also possible. The first input beams **1208, 1308** may have single or multiple wavelengths, and those will be present in the final output beams **1220, 1326** as long as they are wavelengths which the gratings do not diffract. If an input beam does contain a wavelength which a later encountered grating does diffract, rather than be multiplexed it will be de-multiplexed and not appear in the final output beam.

FIG. 26 is a perspective view depicting how planar gratings may also be combined to form a de-multiplexing device **1400** (i.e., a variation of the WDM device **1106** of FIG. 21b). A first planar grating **1402**, a second planar grating **1404**, and a third planar grating **1406** are provided as shown. These may even be the same as the planar gratings **1202, 1204, 1206** of FIG. 22.

An input beam **1408** having four wavelengths (or wavelength ranges)(λ_{1-4}) is provided and may enter the de-multiplexing device **1400**, as shown. As the input beam **1408** passes through the first planar grating **1402** a first diffracted beam **1410** and a first intermediate beam **1412** are produced, wherein the first diffracted beam **1410** will contain one wavelength (λ_1) and

the first intermediate beam **1412** will contain the other wavelengths ($\lambda_{2\text{-}4}$). As the first intermediate beam **1412** passes through the second planar grating **1404** a second diffracted beam **1414** and a second intermediate beam **1416** are produced, wherein the second diffracted beam **1414** will contain one wavelength (λ_2) and the second intermediate beam **1416** will contain the other wavelengths present at this stage ($\lambda_{3\text{-}4}$). As the second intermediate beam **1416** passes through the third planar grating **1406** a third diffracted beam **1418** and an output beam **1420** are produced, wherein the third diffracted beam **1418** will contain one wavelength (λ_3) and the output beam **1420** will contain the other wavelength present at this stage (λ_4)(actually, any wavelengths present that are not diffracted).

FIG. 27 is a perspective view depicting how cubical gratings may similarly be combined to form a de-multiplexing device **1500** (i.e., another variation of the WDM device **1106** of FIG. 21). A first cubical grating **1502**, a second cubical grating **1504**, and a third cubical grating **1506** are provided as shown. These may even be the same as the cubical gratings **1302, 1304, 1306** of FIG. 23.

An input beam **1508** having seven wavelengths (or wavelength ranges)($\lambda_{1\text{-}7}$) is provided and may enter the de-multiplexing device **1500**, as shown. As the input beam **1508** passes through the first cubical grating **1502** a first diffracted beam **1510**, a second diffracted beam **1512**, and a first intermediate beam **1514** are produced, wherein the first diffracted beam **1510** will contain one wavelength (λ_1), the second diffracted beam **1512** will contain another wavelength (λ_2), and the first intermediate beam **1514** will contain the other wavelengths ($\lambda_{3\text{-}7}$). As the first intermediate beam **1514** passes through the second cubical grating **1504** a third diffracted beam **1516**, a fourth diffracted beam **1518**, and a second intermediate beam **1520** are produced, wherein the third diffracted beam **1516** will contain one wavelength (λ_3), the fourth diffracted beam **1518** will contain another wavelength (λ_4), and the second intermediate beam **1520** will contain the other wavelengths present at this stage ($\lambda_{5\text{-}7}$). As the second intermediate beam **1520** passes through the third cubical grating **1506** a fifth diffracted beam **1522**, a sixth diffracted beam **1524**, and an output beam **1526** are produced, wherein the fifth diffracted beam **1522** will contain one wavelength (λ_5), the sixth diffracted beam **1524** will contain another wavelength (λ_6), and the output beam **1526** will contain the remaining wavelength present at this stage (λ_7)(actually, any wavelengths present that are not diffracted).

FIG. 28 is a perspective view depicting how the de-multiplexing device **1400** can be an

integrated unit by simply manufacturing the planar gratings **1402, 1404, 1406** as a single physical unit. The intermediate beams **1412, 1416** are not shown, but will still effectively exist inside the integrated de-multiplexing device **1400**. Similarly, FIG. 29 is a perspective view depicting how the de-multiplexing device **1500** can also be constructed an integrated unit.

The de-multiplexing devices **1400, 1500** in FIG. 26-29 also have a number of similarities. For example, the gratings can be viewed as stages, and there is no reason that fewer or additional such stages cannot be used. The gratings may be tailored to work with specific wavelengths, or wavelengths may be used which work with specific gratings. Combinations of grating types are also possible. The output beams **1420, 1526** may have single or multiple wavelengths, as long as those are wavelengths which the gratings do not diffract.

In the multiplexing device **1200** and the de-multiplexing device **1400** in FIG. 22, 24, 26 and 28 the planar gratings **1202, 1204, 1206, 1402, 1404, 1406** have only been used to each diffract a single wavelength. However, as discussed with respect to FIG. 18-19, planar gratings may actually be used to each diffract two distinct wavelengths, and pass through other wavelengths. Similarly, in the multiplexing device **1300** and the de-multiplexing device **1500** in FIG. 23, 25, 27, and 29 the cubical gratings **1302, 1304, 1306, 1502, 1504, 1506** have only been used to each diffract two distinct wavelengths, and pass through other wavelengths. However, as discussed with respect to FIG. 20, cubical gratings may actually be used to each diffract three distinct wavelengths, and pass through other wavelengths. Accordingly more complex embodiments, based on the principals so far discussed, are also quite feasible.

FIG. 30 is a perspective view depicting a de-interleaver **1600**, a sophisticated de-multiplexing system, according to the present invention. The de-interleaver **1600** includes a center grating block **1602**, a first grating block **1604**, and a second grating block **1606**. The center grating block **1602** includes a number of gratings, which here are cubical gratings **1608a-f** (CG). The first grating block **1604** includes gratings **1610a-f** and the second grating block **1606** includes gratings **1612a-f**. These may be either planar gratings (PG) or cubical gratings (CG), so the gratings **1610a-f, 1612a-f** are generically marked (G) in the figures.

Sets of the gratings **1608a-f, 1610a-f, 1612a-f** here may also be viewed as stages. For example, gratings **1608a, 1610a, 1612a** constitute one set here. The cubical grating **1608a** is used to diffract two wavelengths, but the other gratings **1610a, 1612a** in this stage only have to be able to each diffract one of those wavelengths, and thus may be either planar or cubical. The

following covers this further.

In operation, the de-interleaver **1600** receives an input beam **1614**, from an input source **1616**, and splits that into a first output beam **1618** and a second output beam **1622**, directed here to a first output target **1620** and a second output target **1624**, respectively. The similarities here with FIG. 21b should be noted.

By suitable arrangement of the gratings **1608a**, **1610a**, **1612a** the input beam **1614** here can contain twelve light wavelengths ($\lambda_{1\text{-}12}$), the first output beam **1618** can contain just the "odd" numbered of these ($\lambda_{1,3,5,7,9,11}$), and the second output beam **1622** can contain just the "even" numbered of these ($\lambda_{2,4,6,8,10,12}$). Of course "odd" and "even" are arbitrary distinctions, but they might here, for instance, be odd and even multiples of 100 GHz channels which the inventive de-interleaver **1600** is being used to separate into sets used in a telecommunications system. FIG. 31 is a perspective view depicting how the de-interleaver **1600** may alternately be constructed as an integral unit.

FIG. 32 is a perspective view depicting an interleaver **1700**, a sophisticated multiplexing system, according to the present invention. The interleaver **1700** here purposefully includes the same center grating block **1602**, first grating block **1604**, and second grating block **1606** as appear in FIG. 30-31. This is to emphasize the fact that the interleaver **1700** and the de-interleaver **1600** may be essentially the same. FIG. 33 is a perspective view depicting how the interleaver **1700** may also alternately be constructed as an integral unit.

In operation, the interleaver **1700** receives a first input beam **1702** and a second input beam **1704**, from a first input source **1706** and a second input source **1708**, respectively. The interleaver **1700** then combines these into a single output beam **1710**, which is directed here to an output target **1712**. The similarities here with FIG. 21a should be noted.

While various embodiments have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of the invention should not be limited by any of the above described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

INDUSTRIAL APPLICABILITY

The present multiplexing system **1000** and de-multiplexing system **1100** are well suited for application in the existing and rapidly growing body of applications employing wavelength division multiplexing or de-multiplexing. The inventive systems, as embodiments of fundamentally one underlying invention, have the ability to handle multiplexing or de-multiplexing of as little as one light wavelength, respective to one or multiple others. They also may handle large numbers of light wavelengths concurrently, and this capability is easily scaled to increase the numbers handled. The inventive systems also may have the ability to handle ranges of light wavelengths, somewhat analogous to prior art chirped grating but here in a potentially much more powerful manner. As has been discussed above, the invention employs multi-dimensional gratings and the beneficial properties of the invention can be manifested, if desired, in each optical dimension present.

Another particular strength of the inventive systems over the prior art is that it characteristically separates the paths of the input and output light beams being worked with. This deficiency of the prior art is notorious, and for this reason alone the present multiplexing system **1000** and de-multiplexing system **1100** can be expected to be well received and rapidly applied in the industry.

The inventive systems also well lends themselves to constructing quite complex multiplexing and de-multiplexing systems. The interleaver **1700** and de-interleaver **1600** described above are just two possible examples of this. Once the principals taught herein are grasped, those skilled in the art will appreciate that the multiplexing system **1000**, de-multiplexing system **1100**, interleaver **1700**, de-interleaver **1600**, etc. may be viewed as "building blocks" to construct even more sophisticated systems for multiplexing de-multiplexing. The concept of stages in embodiments, and the scalability this provides are notable in this respect.

The inventive systems may be constructed as physically discrete or contiguously physically integrated embodiments. This facilitates use in a wider range of applications. The use of integrated embodiments also provides other heretofore essentially unavailable benefits, since integrated embodiments inherently have uniform response characteristics. In such an embodiment the relationships between different sets wavelengths being worked with are fixed.

To the extent that there is any change, for instance, a temperature induced one, the relationships between different sets wavelengths will change in concert.

The inventive systems are easily fabricated using conventional and well known materials and micro-fabrication process, but these are used in new manners and in this art where such has not previously been the case done. This contributes to the economy of the invention itself, and the poor economy of the prior art in end applications will also contribute to a rapid and widespread appreciation of the present invention.

For the above, and other, reasons, it is expected that the present invention will have widespread industrial applicability and that the commercial utility of the present invention will be extensive and long lasting.

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